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Land use indicators in life cycle assessment

A case study on beer production

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Abstract
Purpose Inclusion of land use-related environmental aspects into LCA methodology has been under active development in recent years. Although many indicators have been developed and proposed for different aspects of land use (climate change, biodiversity, resource depletion and soil quality), many of indicators have, as yet, not been tested and compared in LCA applications. The aim of this study is to test the different LCIA indicators in practice in a case study of beer production.
Materials and methods Nine different indicators were selected to represent three different impact endpoints of land use: resource depletion, soil quality and biodiversity. The beer production system included all life cycle stages from barley cultivation and the production of energy and raw materials to the serving of beer at restaurant. Several optional system expansions were studied to estimate the possible impacts of substituting feed protein (soybean, rapeseed and silage) with mash coproduct from brewing. A comparison with wine production was also made for illustrative purposes.
Results and discussion The majority of the land use impacts occurred in the cultivation phase, but significant impacts were also found far down the supply chain. The system expansions influenced the overall results markedly, especially for land transformation, soil organic carbon (SOC) and several of the biodiversity indicators. Most of the land use indicators led to results that were consistent with each other. In the inventory and impact assessment phase, challenges were faced in obtaining reliable data. Additionally, the lack of reliable, regional characterization factors limits the usability of the land use indicators and the reliability of the LCIA results, especially of the SOC indicator. None of the studied indicators fulfills all the criteria for an effective ecological indicator, but most have many positive features.
Conclusions All tested land use indicators were applicable in LCIA. Some indicators were found to be highly sensitive to assumptions on land transformation, which sets high requirements for LCI data quality. Scarcity of land use LCI data sources limits validation and cross-comparison. Interpretation of indicator results is complicated due to the limited understanding of the environmental impact pathways of land use.
Recommendations None of the tested indicators describes the full range of environmental impacts caused by land use. We recommend presenting land occupation and transformation LCI results, the ecological footprint and at least one of the biodiversity indicators. Regarding soil quality, the lack of reliable regional data currently limits application of the proposed methods. The criteria of effective ecological indicators should be reflected in further work in indicator development. Development of regionalized characterization factors is of key importance to include land use in LCA.

Keywords Beer · Biodiversity · Indicators · Land use · LCA · Resource depletion · Soil quality

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1 Introduction

Land is a limited resource, and the ongoing competition between forestry, agriculture, infrastructure and natural ecosystems and the continuous increase in the human population are limiting the supply of productive land. Although the current discussion has concentrated mostly on land use impacts caused by biomass production, other processes, such as mining and gravel excavation, also have land use impacts.

Land use is one of the key functions in many systems. It is discussed from different perspectives in different disciplines and fields, which sometimes leads to misunderstandings and confusion. Land use and land use change are reviewed, firstly, in the context of policy and reporting schemes, e.g., reporting according to IPCC (IPCC 2003; IPCC 2006), the EU Renewable Energy Directive (European Union 2009) and PAS 2050 carbon footprint scheme (BSI 2008), and secondly, as a phenomenon affecting several environmental aspects such as climate change, biodiversity and ecosystem services including the productivity of land. In addition, land use and land use change can be considered, for example, from the viewpoints of spatial planning and social aspects. Due to these different approaches, land use-related terminology is diverse. For example, two basic definitions, land cover and land use, are often mixed or used as synonyms. Land cover refers to the physical material on earth's surface, while land use most often refers to the functional dimension and describes how the area is used for urban, agricultural, forestry and other purposes. Land use change refers to the change from one land use category to another, which may lead to a change in land cover; for example, planting forest on land previously used for agriculture. Land transformation can be caused both by human activities and by natural processes. In life cycle assessment (LCA), land use is often referred to as land occupation and land use change as land transformation. To date, there is no established and globally applicable practice on land use occupation and transformation available for use in LCA (EC 2010). Therefore, land use aspects are not generally assessed in LCA studies even in cases in which land use aspects are found to be extremely important such as biofuels (Cherubini and Strømman 2011).

A general framework for land use in LCA has been proposed (Koellner and Scholz 2007; Milà i Canals et al. 2007a) but also criticized (Udo de Haes 2006) due to two main concerns, namely a) the selection of just three main types of impacts related to land use and b) the lack of a critical analysis of whether the selected impacts fit into the methodological structure of LCA. A critical challenge in the practical application of the framework is also the identification of the reference state. Additionally, the framework and terminology themselves are not clearly defined; for example, whether land occupation (land use) and transformation (land use change) refer to inventory data (elementary flows) or midpoint impact categories (see, e.g., Goedkoop et al. 2009). Indicators that can be applied to assess the sustainability of land use have been actively developed both within and outside the LCA community. The indicators proposed cover three land use impact categories: resource depletion, soil quality impacts and biodiversity (Table 1). Despite the abundance of indicators, many of these indicators have not been tested or compared in LCA case studies. The aim of this study is to test these life cycle impact assessment (LCIA) indicators in a case study of beer production. The challenges faced in both inventory collection and result interpretation were studied. Another goal was to compare the indicator results and observe their consistency in highlighting impacts. The robustness of the indicators in the face of possible bias in inventory results is discussed. The final aim of our study was to give recommendations on applying and interpreting land use indicators.

We use "land use" and "land use change" as general terms referring to the phenomena that cause various impacts such as resource depletion, soil quality impacts and changes in biodiversity. Land occupation and land transformation are primarily used as life cycle inventory (LCI) results for other indicators, but they can also serve as resource depletion indicators (i.e., competition for land area). Climate change impacts and indicators are not considered in this study even though they are significant impacts of land use and land use change. The exception to this is the ecological footprint indicator, which includes fossil CO_2 emissions.

Indirect land use change was not considered in this case study, since the focus was on testing different LCIA methods. Indirect land use change is primarily an issue in LCI collection, and the indicators of this study can be used to characterize the results.

2 Materials and methods

2.1 LCI system boundary and data sources

The system boundary for beer production included barley cultivation in Southern Finland, malting and brewing, serving of beer at restaurant, all major raw material and energy inputs, waste water and mash co-product processing, and barley and beer transports (Fig. 1). The main quality requirement set for the inventory data was that land occupation and transformation interventions have to be included in the source data. Primary data was collected only for barley cultivation and for the product flows. For the land use associated with barley cultivation, yield statistics (3,500 kg/ha) were used (FAO 2010). The inputs for barley cultivation were taken from Mäkinen et al. (2006). The industrial land occupation associated with malting and brewing as well as mash processing was assumed to be

Table 1 Some proposed indicators for land use impact categories of resource depletion, soil quality and biodiversity

Land use-related environmental indicator (source in parentheses)	Unit	Land use impact categories	Description
Land use efficiency. Land occupation (e.g., Guinée et al. 2002) and transformation	m^2a/product m^2/product	R	Land occupation and land transformation are primarily used as life cycle inventory (LCI) results for other indicators, but they can also serve as resource depletion indicators (i.e., competition for limited land area).
Ecological footprint (Ewing et al. 2008)	global m^2a	R	Examines the land use competition phenomenon by taking into account the capacity of different land cover types to produce resources for humans. From a resource competition viewpoint, occupying a hectare of cropland is, on average, more resource-consuming than occupying a hectare of marginal pasturelands.
Human appropriation of net primary production (HANPP) (Haberl et al. 2007)	kg C	R, B	Describes the difference in the free NPP left for ecosystems between the current land use and a reference natural state (HANPP = natural state NPP − reduction in NPP − harvested NPP). This difference has been found to correlate well with species diversity.
Ecosystem damage (EDP) (Koellner and Scholz 2006)	unitless	B	Structural diversity can be quantified with the vascular plant habitat-based indicators of the Ecosystem Degradation Potential (EDP).
ReCiPe endpoint hierarchic, Potentially Disappeared Fraction (PDF) of species (Goedkoop et al. 2009)	species year	B	Considers biodiversity damage as the Potentially Disappeared Fraction (PDF) of species in a given region based on the diversity of vascular plants. The damage is calculated as the difference in species richness in the occupied case compared to the reference state, which is considered to be woodlands in Europe.
Threats to endangered species (Lenzen et al. 2009)	unitless	B	Build on a global regression between species endangerment and land use resulting in broad set of correlation coefficients for land use occupation and threats to birds, mammals, plants, reptiles, and amphibians. The coefficients can be used as an approximation for the threat to endangered species and presented in ready characterization factors.
Solar exergy dissipation SED (Wagendorp et al. 2006)	%	B	A functional biodiversity indicator based on the extent of solar exergy dissipation (SED). The underlying concept is to monitor the surface temperature of different ecosystems in similar conditions. The ecosystem emitting less heat dissipates more exergy. SED can be seen as an indicator of the sustainability of the current occupation at landscape level.
Changes in soil organic carbon SOC and soil organic matter SOM (Milà i Canals et al. 2007c; Brandão et al. 2010)	kg C year/m^2 year	S, (C)	SOC/SOM has been proposed as a soil quality indicator in LCA as it is often reported and is closely related to many other soil quality indicators such as cation exchange capacity and soil life activity.
LANCA method (Beck et al. 2010)	several	S	Method for calculating several essential land functions (e.g., erosion resistance, filtration potential, and groundwater recharge) to determine the potential impacts of the studied activity on the ecological quality of land. Calculation based on detailed site-specific data. Applied in LCI phase, not a characterization model for LCIA phase.

R resource depletion, *S* soil quality, *B* biodiversity, *C* climate change

insignificant (i.e., they were cut off). The primary data for malting and brewing was based on the environmental reports of Carlsberg (2005). Secondary data was used for energy and raw material inputs, waste water treatment and glass manufacture in the beer production system (see Fig. 1). The data was collected from the Ecoinvent 2.2 database (Ecoinvent 2010). To our knowledge, it is currently the only LCI database that includes upstream land occupation and transformation data that is in suitable format for all the land use indicators proposed for this study.

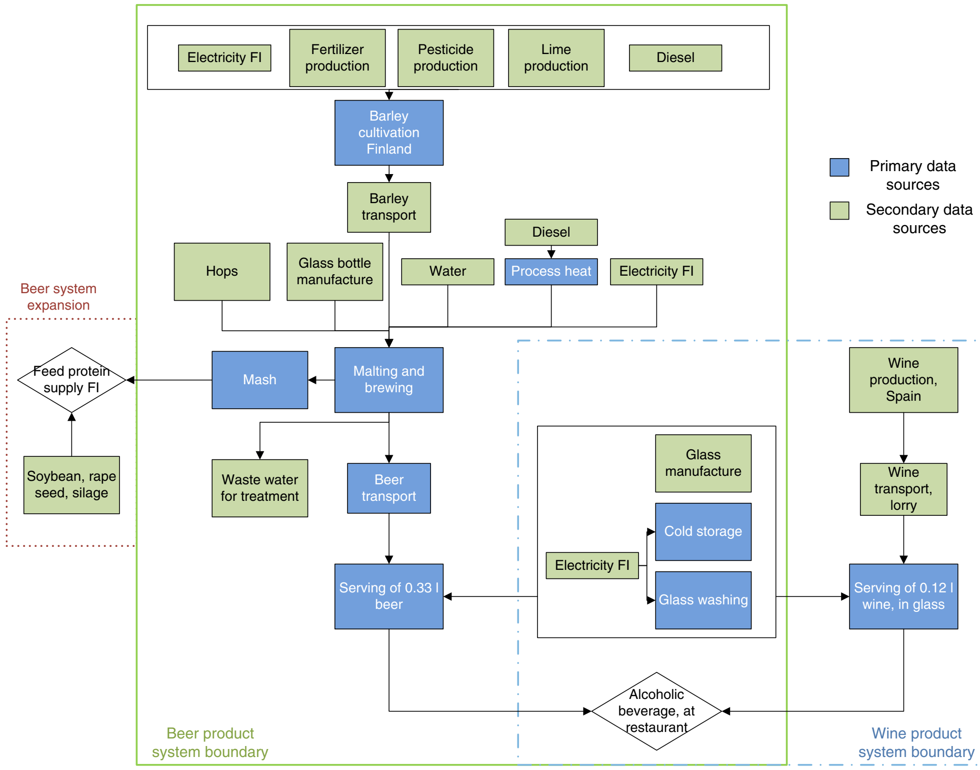

Fig. 1 System boundary of the study. The *green (uniform) line* delimits the beer product system boundary, the *red (dotted) line*, the system expansion for the beer product system and the *blue (dashed) line*, the wine product system boundary. Some processes belong to both beer and wine product systems and, therefore, the system boundaries overlap. Note: the wine production process includes only the land use inventory data for grape cultivation (Gazulla et al. 2010)

The Finnish power supply mix (Ecoinvent 2.2 covers the years 1992–2004) was used for electricity use in Finland. All the secondary data collected from Ecoinvent includes built-in assumptions for upstream electricity production and the land occupation and transformation of each separate process. No recycling was assumed for the bottles. See Online Resource 1 for a complete list of LCI data.

Mash is a major coproduct of the brewing process, with an output of approximately 0.15 kg per 1 l of beer bottled (Carlsberg 2005). In Finland, the mash co-product is sold for use in animal feed processing (Suomen Rehu 2010). Mash was assumed to substitute primarily other sources of protein supplements in the feed. Several optional system expansions (soybean, rapeseed and silage) were tested to study the possible impacts of the substitution (see Fig. 1).

A comparison was made to wine production (see Fig. 1) on the basis of values from a recent LCA study for Spanish wine production (Gazulla et al. 2010). Although the study covers the whole life cycle of wine production, the LCI data on land use includes only grape cultivation, but no data about the wine production processes (e.g., production of raw materials, energy or the wine itself). Therefore, the comparison is shown for illustrative purposes only. The comparison was made based on the functional unit of one portion of alcohol[1] served in Finnish restaurant, equaling 0.33 l beer or 0.12 l wine.

[1] One portion of alcoholic beverages is a standardized measure in Finland and equals 11–15 g of alcohol (Valvira 2008).

2.2 Characterization factors chosen

The indicators presented in the literature were selected to represent the three main impact endpoints of land use (see Table 1). Only those indicators that are presented as LCIA characterization factors and those that could be adapted to that purpose were applied. This excluded the use of biodiversity indices from conservation biology (Scholes and Biggs 2005). Some indicators would have required detailed site assessments, which were found to be unfeasible for the whole life cycle considered and were, therefore, excluded. This resulted in the exclusion of the otherwise promising Biotope method (Rydgren et al. 2005) and the ecosystem functioning-based multiindicator set (Achten et al. 2009). The LANCA method (Beck et al. 2010) proposed for soil quality impact assessment requires that the user determine five soil quality parameters during the LCI phase based on an extensive amount of site-specific soil quality parameters, and no characterization in the LCIA phase is possible. Operationalization of the method by Saad et al. (2011) was not included in this study due to the extensive level of detail needed. Additionally, access to country level averages (PE-GaBi 2011) was limited. Overall, this selection process resulted in the testing of nine indicators as described below.

For soil quality, the approach of Milà i Canals et al. (2007c) was used. Damage is modeled as the time-integrated difference in soil organic carbon (SOC) content between the studied land cover and a reference state

(woodland). The SOC indicator does not cover all aspects of ecological soil quality. Soil erosion, compaction, build-up of toxic substances, acidification, salinization, and depletion of nutrients and ground water are soil quality aspects that need to be covered with other indicators in LCIA (Milà i Canals et al. 2007b). Furthermore, these aspects impact functional properties of soil and, therefore, also soil biodiversity. The LANCA method (Beck et al. 2010) partially covers these aspects but was not applied in this study due to the reasons previously mentioned. For the resource depletion aspect of land use, the ecological footprint was used. Occupied land area was weighted by the productivity index (i.e., equivalence factor) of that land type. Average global productivities (Ewing et al. 2008) were used instead of country-specific ones, since the locations of individual processes in the LCI were unknown.

Biodiversity was described with indicators of both structural and functional diversity. Structural diversity was quantified with the vascular plant habitat-based indicators of the Ecosystem Degradation Potential (EDP) (Koellner and Scholz 2006), the Potentially Disappeared Fraction used in the ReCiPe LCIA characterization set (Goedkoop et al. 2009) and indicators used in individual studies (Schmidt 2008). Since vascular plants represent only a fraction of biodiversity, the impacts to other species were included with the recent correlations between land cover and endangerment of birds, mammals, plants, reptiles and amphibians (Lenzen et al. 2009). For functional diversity, two indicators were used: solar exergy dissipation (SED) (Wagendorp et al. 2006) and human appropriation of net primary production (HANPP) (Haberl et al. 2007). Both indicators measure the influence of human activity on the energy flows of the ecosystem. These indicators had to be modified prior to use. For SED, the distance to the reference state (mature forest) was calculated using values published in Wagendorp et al. (2006). For HANPP, the net primary productivity and the human harvesting ratios were applied to the boreal conditions as described in Mattila et al. (2011).

3 Results and discussion

3.1 Challenges in obtaining inventory and impact assessment data

The collection of reliable inventory data for land occupation and transformation proved to be challenging. Comparable inventory data could not be found for the beer and wine systems. The Ecoinvent (2010) database includes LCI data for land occupation and transformation. However, the transparency of system boundaries and assumptions is often challenging when using inventory data from databases. Individual reports and research articles are usually more transparent with respect to system boundaries and assumptions, but the drawback is that only the LCI data on land occupation is usually included. In addition, the PE-GaBi database (2011) includes several land quality parameters as inventory flows based on the LANCA method (Beck et al. 2010) but does not include LCI data on land occupation (m^2a) and transformation (m^2) with sufficient coverage.

Raw material cultivation was identified as being responsible for the majority of land occupation in the case of both beer and wine production (Fig. 2). Permanent vine crop cultivation for wine and arable land for barley cultivation for beer are the main land categories occupied. However, the use of LCI data from Ecoinvent (2010) led to some surprising results. For example, glass bottle production contributed to 35% of the land occupation in the beer production system through the occupation of forestland (see Fig. 2). The reason behind this forestland occupation was the need for wooden pallets in the transport of the bottles. Another surprising result was the impacts related to the land transformation of rainforests in soybean substitution (Fig. 3). The avoided soybean production leads to the avoidance of the clearance of tropical rain forest and sclerophyllous shrubland for use as arable land for soybean cultivation. Since Ecoinvent is the only source for LCI data on land occupation and transformation for a wide set of processes, checking for potential errors and unrealistic assumptions in this data would improve the quality and reliability of future LCA studies that include environmental impacts of land use.

A relatively small amount of processes account for the majority of land use impacts in the beer product system. Barley cultivation is responsible for approximately 60–80% of the environmental impacts regardless of the indicator, glass bottle production for about 15–20% and the rest of the life cycle for approximately 5–20% (Fig. 4). This indicates

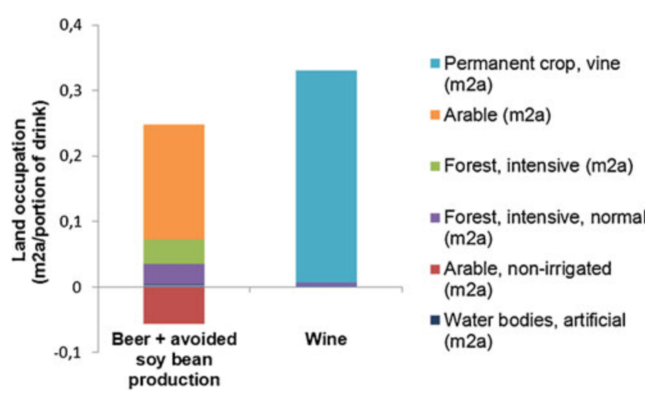

Fig. 2 Land occupation of beer and wine product systems divided by land category. Avoided land occupation is the result of system expansion (avoided soybean meal production by material substitution). Note: the system boundaries of the two systems are not fully comparable

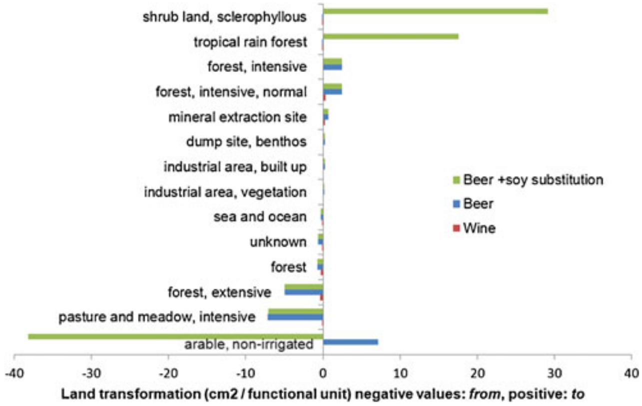

Fig. 3 Land transformation impacts (direct) of beer and wine product systems divided by land category. Results for beer are presented with and without system expansion for soybean production. Negative values indicate a decrease in a certain land use category (i.e., from) and positive values an increase in a land use category (i.e., to)

that the inclusion of only the land use inventory data related to the cultivation phase in LCA studies for biomass-based products (in, e.g., Gazulla et al. 2010) could lead to significant cutoffs in terms of land use-related environmental impacts. An example is the unexpected result that glass bottle production has significant land use-related environmental impacts in the life cycle of beer production. Hence, care should be taken when cutoffs are applied in the LCI phase.

There were also difficulties related to the data needed for some impact assessment indicators. Problems were faced especially in the calculation of case-specific characterization factors for the SOC indicator. No reliable data could be found for the state and evolution of the regional SOC levels. Therefore, the SOC characterization factors provided in Milà i Canals et al. (2007b) were applied in this study, but the results obtained might be biased because the generalized reference SOC level (forestland in the United Kingdom) was used in the Milà i Canals et al. (2007b) study. This was especially problematic because the SOC level in the reference state has a key impact on the total SOC indicator result. The lack of reliable data on regional SOC reference levels currently limits the usability of the method, since the LCA practitioner would need to use correct SOC reference data for the region studied.

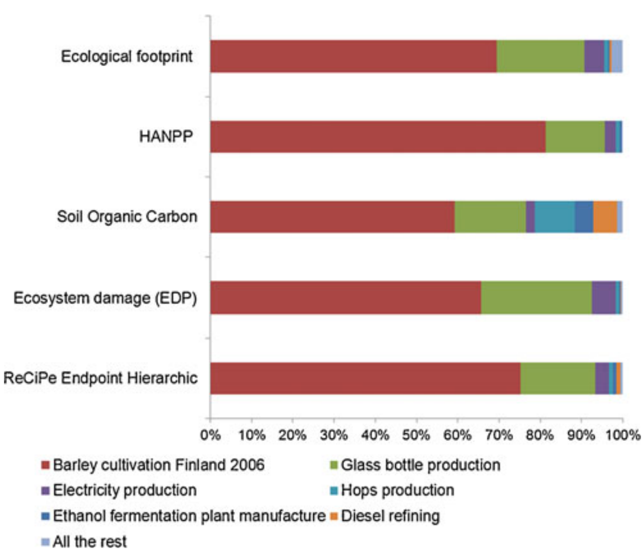

Fig. 4 The impact of individual life cycle phases (i.e., processes) on the total land use indicator result for a selection of LCIA indicators for the beer product system with no system expansions. The contribution of each life cycle phase is presented as a relative share [%] of the selected indicator result

An additional challenge is the wide geographic spread of the different processes in the life cycle. Only a part of the life cycle takes place in the region where the final product is produced. Therefore, it is questionable to apply the characterization factors derived from data for some region to all the processes, e.g., for soybean from South America. Therefore, different characterization factors would be needed for each region. The SOC characterization model (Brandão et al. 2010) is a good example, but the requirement for more site-specific LCIA factors and reference levels is not unique for this indicator. This challenge applies also to most of the other LCIA factors considered, especially HANPP, SED, EDP and the ecological footprint. The need for site-specific LCIA, as identified earlier by (Hauschild 2006), is especially relevant for land use, where the local conditions may vary considerably from regional averages. One solution would be to make different characterization sets for all of the world's 867 terrestrial ecoregions (WWF 2010), and this type of development work is already being done within the LCA community.

3.2 System expansion influenced the overall results

The choice of system expansion for the produced mash had a particularly significant influence on land transformation and some biodiversity indicators (Table 2). When soybean or rapeseed was substituted, the area of natural land transformed to cultivated land that was avoided was larger than that transformed by the beer production system itself (see Table 2, Fig. 3). One reason for this was the assumptions of land transformation in the Ecoinvent database, in which the historical land use change is allocated to different products (i.e., indirect land use is not included). In these data, soybean cultivation partially replaces tropical rainforest and shrubland, while rapeseed replaces long-term fallows in Europe. Another reason for the proportionally large influence of system expansion was that land transformation was ignored for barley cultivation (based on the statistics for overall field areas). The influence of system expansion on LCI results on land occupation was less significant and was caused mainly by

Table 2 The effect of system expansion for mash protein on the LCIA result. Results were internally normalized to the nonexpanded system. Negative indicator results reflect avoided impacts, i.e., net gain. Differences larger than 100% are marked in bold

		Beer				Wine
		Avoided soy	Avoided rapeseed	Avoided silage	No expansion	
Resource depletion	Land occupation	76%	83%	78%	100%	132%
	Land transformation	**−3,483%**	**−1,222%**	**−153%**	100%	3%
	Ecological footprint	76%	83%	95%	100%	137%
Soil quality	Soil organic carbon (SOC)	5%	**−75%**	65%	100%	53%
Biodiversity	Ecosystem damage (EDP)	**−774%**	84%	82%	100%	117%
	ReCiPe PDF	**−2,361%**	82%	80%	100%	93%
	Brentrup2002 NDP	73%	81%	84%	100%	133%
	Lenzen2009 birds	56%	70%	93%	100%	**243%**
	Lenzen2009 mammals	75%	83%	87%	100%	140%
	Lenzen2009 plants	66%	77%	98%	100%	186%
	Lenzen2009 reptiles	75%	83%	104%	100%	137%
	Lenzen2009 amphibian	70%	79%	75%	100%	167%
	Schmidt2008 vascular plants	74%	82%	79%	100%	122%
	Solar exergy dissipation	70%	79%	80%	100%	173%
	HANPP	73%	81%	91%	100%	51%

Indicators are present in several impact categories. See Tables 1 and 3

differences in the protein yield of different crops (i.e., grams of protein produced per hectare).

Two of the biodiversity indicators were highly sensitive to the assumptions on avoided land transformation. Ecosystem damage potential (EDP) and the Potentially Disappeared Fraction (PDF) of species were especially sensitive to natural forest transformation. If soybean was substituted by mash protein, the overall biodiversity impacts of beer production were negative, indicating biodiversity gain. Since no tropical rainforest transformation was avoided in the substitution of rapeseed or silage, the biodiversity gains were less than 20% of the whole impact. The sensitivity of the LCIA methods to tropical rainforest transformation is significant, since in the case study in which mash coproduct replaces soybean cultivation, the avoided area of tropical rainforest clearance was 18 cm^2 per portion of alcohol while the area occupied by barley cultivation was 1,753 cm^2 per portion of alcohol. Therefore, both EDP and PDF are extremely sensitive to assumptions concerning the supply chain that are connected to tropical rain forests. Since the connections can be very far down the supply chain, the inventory results have to be carefully checked when interpreting the results.

In contrast, the other biodiversity indicators focus only on land occupation and are considerably more robust to the selection of system expansion. With most indicators, the difference between the system expansions was less than 30% of the original result. Also, most indicators had a consistent outcome: the avoidance of soybean offered the greatest benefits while the avoidance of silage resulted in only minor benefits. When the indicator for reptiles was considered, the avoidance of silage even resulted in increased damage.

Resource use indicators were not as sensitive to system expansion as the biodiversity indicators. The differences between substitution alternatives were about 20% with HANPP and the ecological footprint. Both indicators gave more credits from the substitution of rapeseed than from silage, although silage substitution resulted in less land occupation. This is a result of the higher productivity and higher share of NPP used in rapeseed fields than in silage production.

SOC was sensitive to substitution assumptions. The SOC change due to substituting rapeseed resulted in negative overall impacts (i.e., increases in SOC levels), since rapeseed cultivation was assumed to replace high soil carbon pastures in the Ecoinvent datasets. A similar benefit was obtained for tropical rainforest transformation, but to a lesser extent, and for silage the benefits were even smaller. Similar to EDP and PDF, the SOC indicator was also found to be sensitive to assumptions on avoided land transformation.

Regardless of system expansion choice, beer was preferable to wine for all indicators, except HANPP and SOC. The HANPP indicator result for wine production differs from the other resource use indicator results because it includes the competition for human-usable biomass with other heterotrophic (i.e., nonphotosynthesizing) species. Vine is a perennial plant and only a small portion of the biomass (the grapes) is collected for wine production. This

Table 3 Main pros and cons of tested land use indicators

Indicator	Impact category covered	Pros	Cons
Land occupation	R (B, S)	+ Easy to understand	- Does not indicate if land use impacts are beneficial or negative for the environment
		+ Low uncertainty + Serves also as LCI data for several other indicators	- Because there is no characterization on different land use categories, it is difficult to interpret the indicator if different land use categories are summed up
Land transformation	R (B, S)	+ Easy to understand and applicable from policy perspective (e.g., forest footprint)	- May be difficult to interpret whether the specific transformation is beneficial or negative
		+ Serves also as LCI data for several other indicators	- Classification of land use categories is often too coarse to describe the impacts of land use management, and intensive/extensive classification could be further developed
			- High uncertainties related to inventory due to dynamic phenomena
			- Difficult to identify and allocate correctly the cause–effect chains
Ecological footprint	R	+ Often used indicator outside the LCA community	- Not transparent how land use and CO_2 emissions are combined in the indicator
		+ Data available on country level + Easy to calculate and interpret (occupation of productive land)	- Does not include land use change
		+ Normalization easily understandable (limits of the Earth)	
Human appropriation of net primary production (HANPP)	R, B	+ Correlates well with biodiversity (measured)	- The unit (kg C) is difficult to interpret
		+ Strong theoretical background	- Difficult to apply in LCA that covers processes in many countries
			- Covers mainly biodiversity of plants
			- Does not include land use change
Ecosystem damage (EDP)	B	+ Has a strong theoretical and empirical background	- Is based on Central European data and, thus, application elsewhere may lead to distorted results
		+ Is connected to nature conservation	- Covers only plants
			- Unitless and, therefore, difficult to understand
ReCiPe endpoint hierarchic, Potentially Disappeared Fraction (PDF) of species	B	+ Has a strong theoretical and empirical background	- Is based on Central European data and, thus, application elsewhere may lead to distorted results
		+ Is connected to nature conservation	- Covers only plants
			- Is highly sensitive to land use changes occurring in rain forests
Threats to endangered species	B	+ Easy to interpret	- Low (coarse) resolution in land use types
		+ Can be connected to nature conservation + Includes also animals	- No regional specification (global level indicator)
Solar exergy dissipation (SED)	B	+ Strong theoretical basis and framework	- Difficult to understand, interpret and communicate
			- Difficult to combine with other indicators
			- Difficult to inventory and assess in large regions
Changes in soil organic carbon (SOC) and soil organic matter (SOM)	S	+ Easy to interpret in theory	- Unit is not clear (kg C a m^{-2} a^{-1}) and misinterpretations occur easily
		+ High policy relevance	- Very sensitive to selected reference
			- Difficult to apply at the global level due to local data needs

R resource depletion, *S* soil quality, *B* biodiversity

differs significantly from barley cultivation, in which most of the net primary production is harvested annually.

3.3 Interpreting indicators in relation to sustainable land use

In general, indicators are used for assessing and reporting past trends and supporting future decision-making processes. To be effective, an ecological indicator should provide relevant information about changes, be sensitive, be able to detect changes at the appropriate temporal and spatial scale, be based on well-understood and generally accepted conceptual models of the system, be based on reliable data that are available to assess trends and are collected in a relatively straightforward process, be based on data for which monitoring systems are in place and be easily understood by policy-makers (Millennium Ecosystem Assessment 2005). None of the studied indicators fulfill all the criteria for an effective ecological indicator, but most have many positive features (Table 3). Only the solar exergy dissipation (SED) indicator was considered to be very challenging in many respects. As land use and land use change cover a wide area of impacts on resource use, soil quality and biodiversity, it is obvious that individual indicators are not sufficient to describe the whole land use impact. In spite of this, most LCIA characterization sets include only one indicator for land use (EC 2010). Based on the results of this study, we recommend that a set of indicators should be compiled to cover all three of the impact areas using the principles of effective ecological indicators (Millennium Ecosystem Assessment 2005). However, due to a general and perhaps also structural problem of LCA, the criteria for detecting changes at the appropriate temporal and spatial scale can be difficult to solve. In many cases, land use-related data is only available on the average level and from a historical perspective, and therefore, spatial and temporal changes are difficult to detect, even though method development is ongoing within the LCA community.

4 Conclusions and recommendations

Different LCIA indicators were tested in an illustrative case study from a practitioners' (e.g., consultants and businesses) point of view. The published indicators could be applied, and they provided information for the comparison of product alternatives. Challenges in inventory collection included the lack of diverse data sources. For the most part, a single database was used for LCI, which limits the validation and cross-comparison of data. The need for primary data (e.g., site-specific) or secondary data (e.g., regional data from databases) depends on the goal and scope of the study. If the goal is general hotspot analysis of certain activities (e.g., beer production in Europe), then secondary LCI data can be used. For most indicators, most of the impacts were caused in the cultivation phase. However, major impacts were also found far down the supply chain (e.g., wood pallets used for glass transportation). As is common in LCA, the choice of system boundaries was shown to influence the overall result considerably. EDP and PDF indicators were found to be highly sensitive to assumptions on land transformation, and this sets high requirements for LCI data quality. The interpretation of indicator results is complicated by the limited understanding of the land use phenomenon and its environmental impact pathways. As a consequence, no single indicator was found to describe the full range of environmental impacts caused by land use. Based on the results, we recommend presenting land occupation and transformation LCI results, the ecological footprint and at least one of the biodiversity indicators. Regarding soil quality, the lack of reliable regional data currently limits application of the proposed methods. The LCA practitioner would need to use correct activity and reference data for the region studied. The criteria of effective ecological indicators of the Millennium Ecosystem Assessment should be used in further work in indicator development.

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